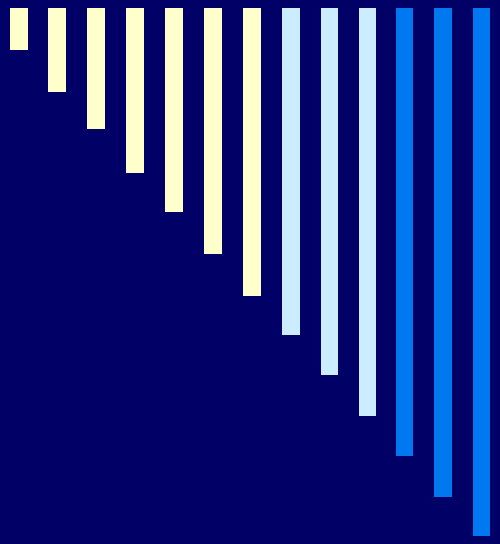


The Scale of the Universe

Astrophysics

April 26, 2005

Measuring Space

- Our part of Universe has at least three independent directions of separation
- Separation determined by a length scale
- In Newtonian theory, there are three independent units: Length, Time, & Mass
- In Einstein's General Relativity (GR), all physical quantities are measureable in length units

The Universe as a Metric Space

- Separations can be measured.
  (old: meter; new: light distance)
- In weak gravity, Euclidean axioms "work", e.g.

$$c^2=a^2+b^2 \rightarrow ds^2=dx^2+dy^2+dz^2 .$$

- In Einstein's GR, separation between events is

$$ds^2= \Sigma g_{\mu\nu} dx^\mu dx^\nu .$$

$g_{\mu\nu}$ is called the metric tensor.

Measuring distances “nearby”

- Direct measure or by reflected light
- Moon: Laser reflector left by astronauts
- Planets: Parallax and radar reflection
- Sun: With planets and Newton
- Nearby stars: Parallax

  Hipparcos satellite: About 1,000 LY

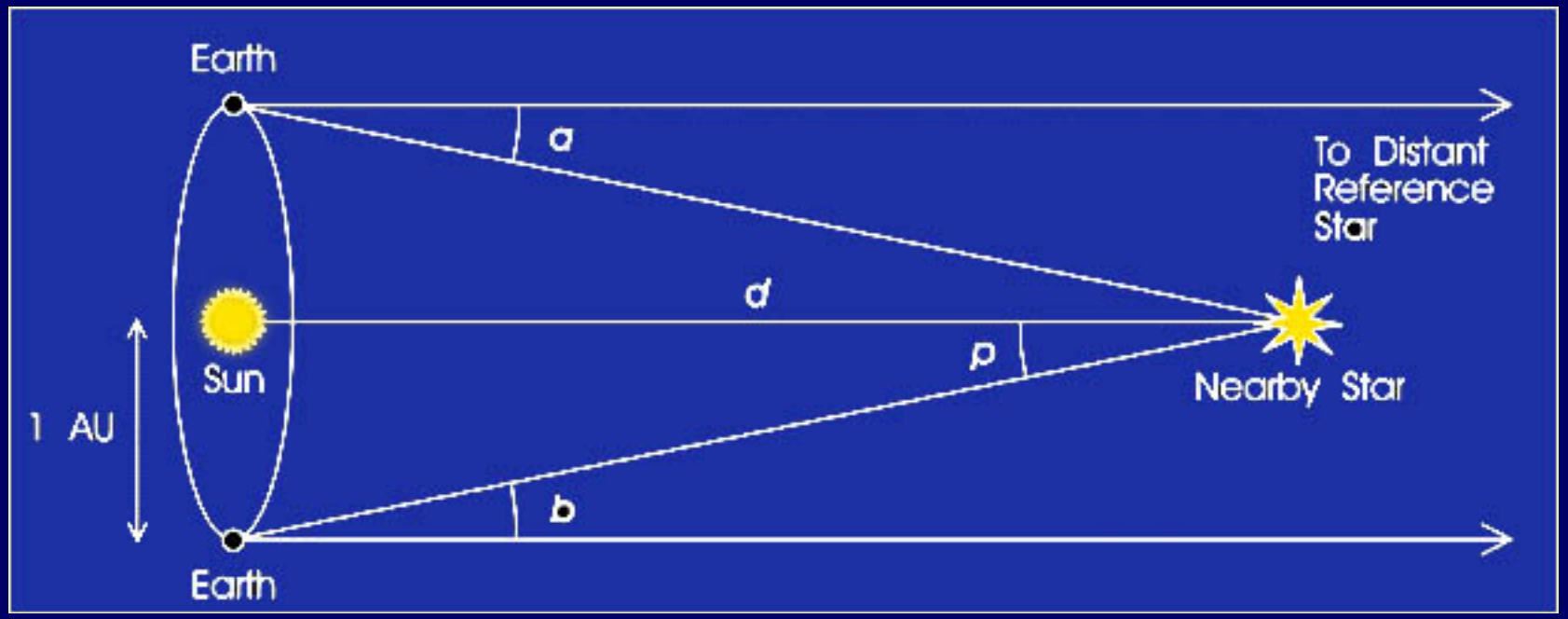
  GAIA satellite (2010) 50,000 LY

Global Astrometric Interferometer for Astrophysics (GAIA) (*http://astro.esa.int/gaia/*)

Distance to nearby stars

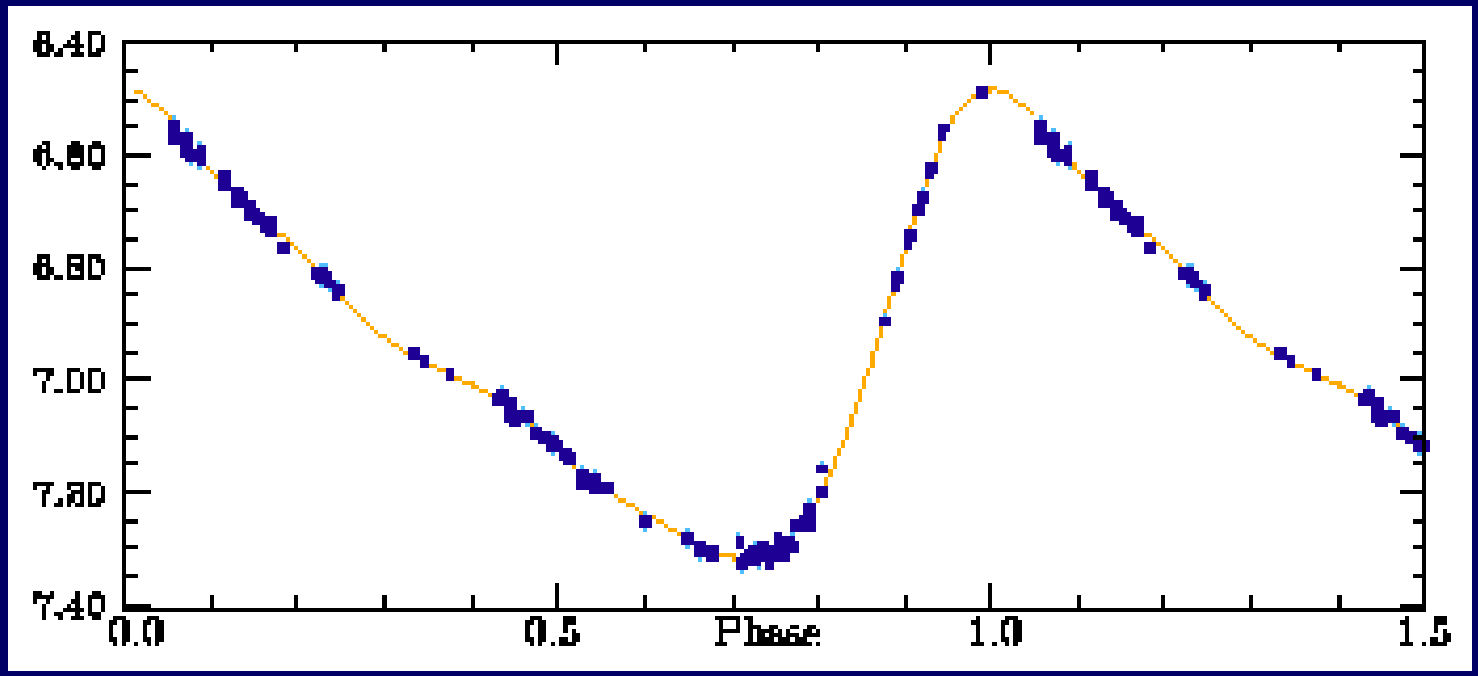
By Parallax

$$p = \frac{1\,AU}{d}\,radians = {}^{206265''}\!/_{d}$$



Measuring distance to far stars and nearby galaxies

- Cepheids found in 1912 by Henrietta Leavitt to have a period-luminosity relation



Getting distance via cepheids

Measure period P and relative magnitude m, then find

$M = -2.59 \log (P/\text{day}) - 0.67$

$d = 10\text{pc}\ 10^{((m-M)/5)}$

Galactic distances via Cepheids

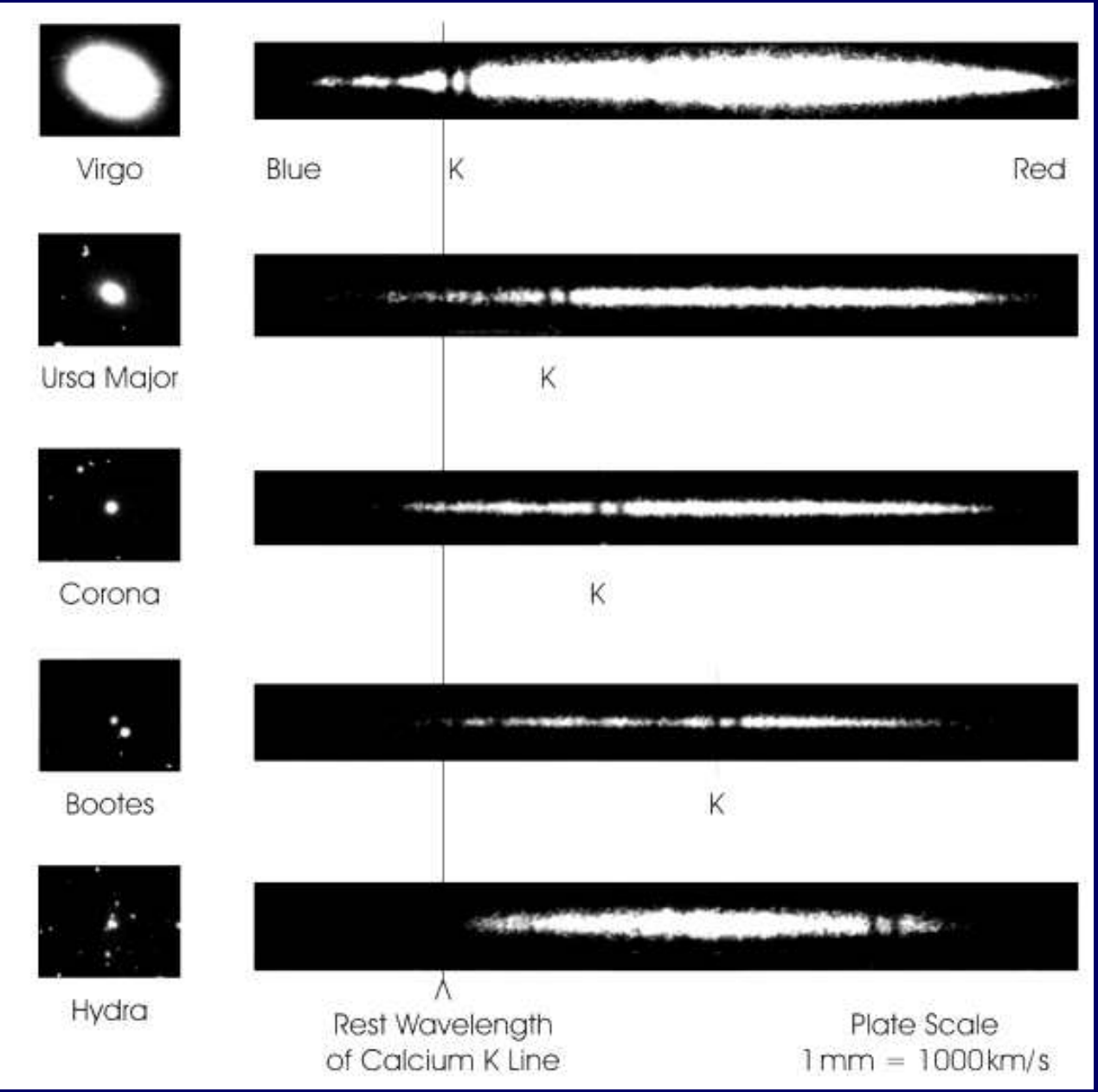
- Edwin Hubble found Andromeda was another galaxy in 1924
- In 1929, Hubble found distance/redshift relation for galaxies

$$z = \Delta\lambda/\lambda = (H_o/c)\, d$$

For low velocities, z = v / c.

General: z = sqr[(1+v/c)/(1-v/c)]-1.

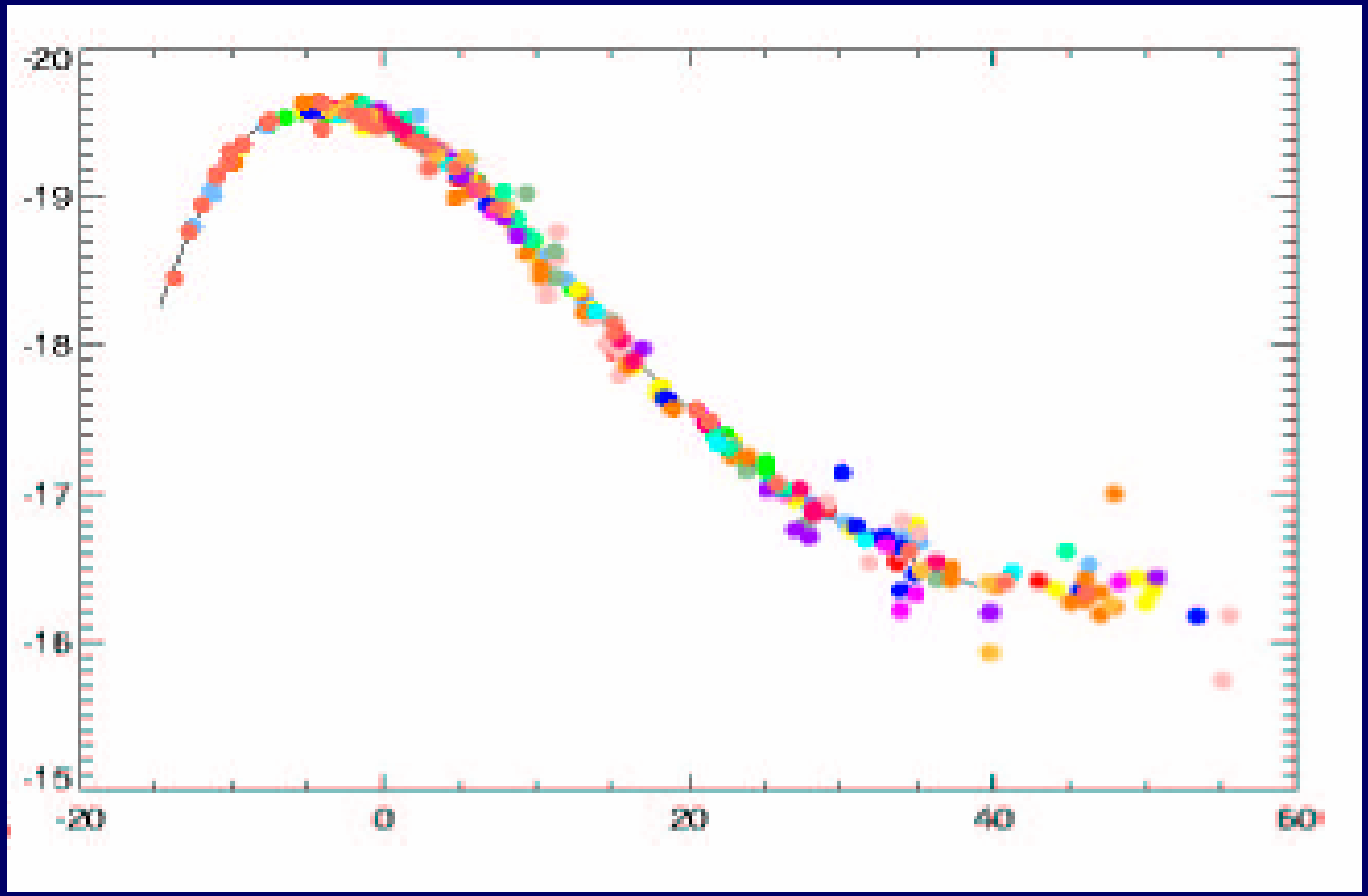
Doppler shift in spectra of galaxies



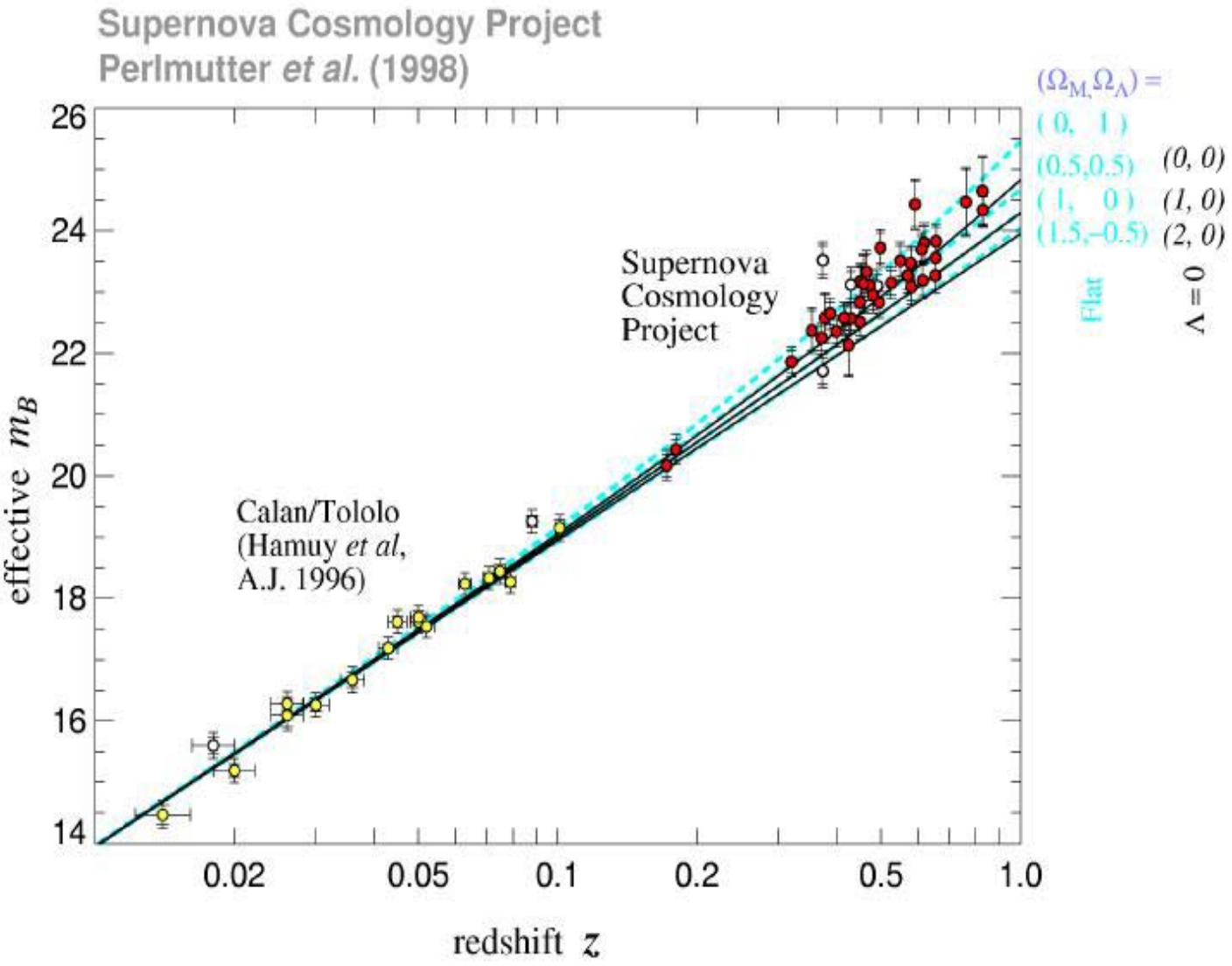
Galactic distances via SN Ia

- All supernovae I a (binary systems) have nearly the same maximum brightness!

Supernovae magnitude vs days:



Latest Hubble type plot

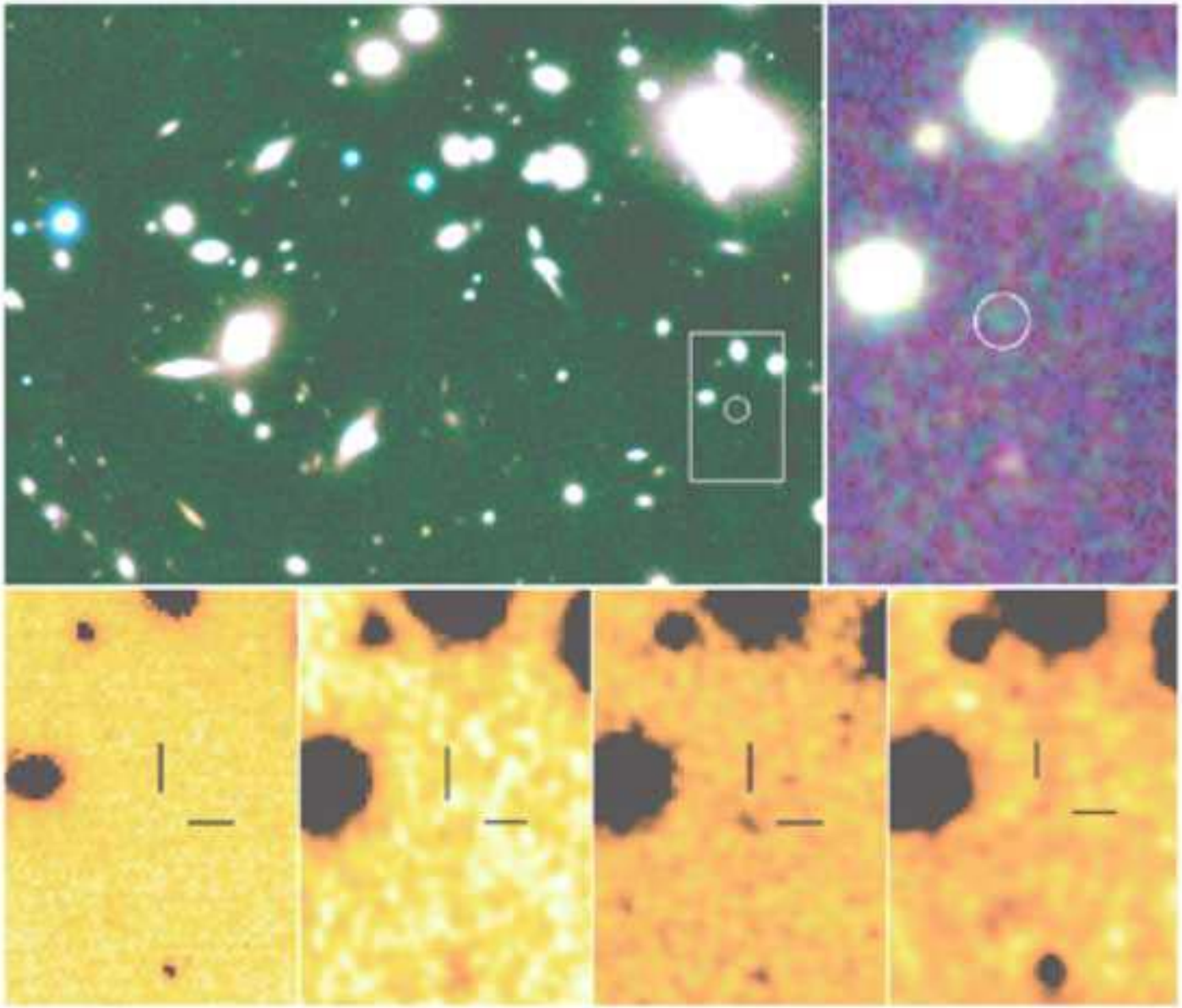


In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe: 1%

Galaxy 13.23 Billion LY away!

- In March 2004, ESO announced that a newly discovered galaxy named Abell 1835 IR1916, has a redshift of 10. Using Hubble's Law, the galaxy is found to be 13 230 million light-years away. We see the galaxy as it was when the Universe was only 470 million years old. That is only 3 percent of its current age. These results were determined by spectral analysis of its light.



Abell 1835 IR1916 - the Farthest Galaxy - Seen in the Near-Infrared
(VLT ANTU + ISAAC)

ESO PR Photo 05a/04 (1 March 2004)

Modern form of Hubble's law

From Friedmann-Robertson-Walker metric in General Relativity:

$$D_L = \frac{(1+z)c}{H_0\sqrt{|\Omega_\kappa|}} S\left\{\sqrt{|\Omega_\kappa|}\int_0^z \left[\Omega_\kappa(1+z')^2 + \Omega_M(1+z')^3 + \Omega_\Lambda\right]^{-1/2} dz'\right\}$$

$$\Omega_M = \frac{8\pi G}{3H_0^2}\rho_M \qquad \Omega_k = -\frac{kc^2}{R^2H_0^2} \qquad \Omega_\Lambda = \frac{\Lambda c^2}{3H_0^2}$$

S(x)=sin(x) for k=1, sinh(x) for k=-1, x for k=0